DTIC FILE COPY

(4)

OFFICE OF NAVAL RESEARCH

AD-A213 732

Contract N00014-86-K-0043

TECHNICAL REPORT No. 113

Interface Phonons in Semiconductor Double Heterostructures

by

D. L. Lin, R. Chen and Thomas F. George

Prepared for Publication

in

Solid State Communications

Departments of Chemistry and Physics
State University of New York at Buffalo
Buffalo, New York 14260

October 1989



89 10 16 171

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

# REPORT DOCUMENTATION PAGE

*Form Approved OMB No. 0704-0188*

| | |
|---|---|
| 1a. REPORT SECURITY CLASSIFICATION<br>Unclassified | 1b. RESTRICTIVE MARKINGS |
| 2a. SECURITY CLASSIFICATION AUTHORITY | 3. DISTRIBUTION/AVAILABILITY OF REPORT<br>Approved for public release; distribution unlimited |
| 2b. DECLASSIFICATION/DOWNGRADING SCHEDULE | |
| 4. PERFORMING ORGANIZATION REPORT NUMBER(S)<br>UBUFFALO/DC/89/TR-113 | 5. MONITORING ORGANIZATION REPORT NUMBER(S) |
| 6a. NAME OF PERFORMING ORGANIZATION<br>Depts. Chemistry & Physics<br>State University of New York<br>6b. OFFICE SYMBOL *(If applicable)* | 7a. NAME OF MONITORING ORGANIZATION |
| 6c. ADDRESS *(City, State, and ZIP Code)*<br>Fronczak Hall, Amherst Campus<br>Buffalo, New York 14260 | 7b. ADDRESS *(City, State, and ZIP Code)*<br>Chemistry Program<br>800 N. Quincy Street<br>Arlington, Virginia 22217 |
| 8a. NAME OF FUNDING/SPONSORING ORGANIZATION<br>Office of Naval Research<br>8b. OFFICE SYMBOL *(If applicable)* | 9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER<br>Contract N00014-86-K-0043 |
| 8c. ADDRESS *(City, State, and ZIP Code)*<br>Chemistry Program<br>800 N. Quincy Street<br>Arlington, Virginia 22217 | 10. SOURCE OF FUNDING NUMBERS<br>PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO / WORK UNIT ACCESSION NO. |

11. TITLE *(Include Security Classification)*

Interface Phonons in Semiconductor Double Heterostructures

12. PERSONAL AUTHOR(S)

D. L. Lin, R. Chen and Thomas F. George

| 13a. TYPE OF REPORT | 13b. TIME COVERED | 14. DATE OF REPORT *(Year, Month, Day)* | 15. PAGE COUNT |
|---|---|---|---|
| | FROM ______ TO ______ | October 1989 | 14 |

16. SUPPLEMENTARY NOTATION

Prepared for publication in Solid State Communications

| 17. COSATI CODES | | | 18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)* | |
|---|---|---|---|---|
| FIELD | GROUP | SUB-GROUP | INTERFACE PHONONS | DISPERSION RELATIONS |
| | | | SEMICONDUCTORS | EIGENVECTORS |
| | | | DOUBLE HETEROSTRUCTURES | RAMAN SCATTERING |

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

Within the framework of the continuum model, the equation of motion for the polarization vector in a semiconductor double heterostructure is solved exactly for the interface phonon modes. Both the eigenvectors and dispersion relations are obtained analytically. It is shown that the slab modes observed in right-angle Raman scattering in a GaAs quantum can be understood in terms of the interface modes found in this paper.

| | |
|---|---|
| 20. DISTRIBUTION/AVAILABILITY OF ABSTRACT<br>☒ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS | 21. ABSTRACT SECURITY CLASSIFICATION<br>Unclassified |
| 22a. NAME OF RESPONSIBLE INDIVIDUAL<br>Dr. David L. Nelson | 22b. TELEPHONE *(Include Area Code)*<br>(202) 696-4410<br>22c. OFFICE SYMBOL |

DD Form 1473, JUN 86 *Previous editions are obsolete.*

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

Solid State Communications, in press

# Interface Phonons in Semiconductor Double Heterostructures

D. L. Lin, R. Chen and Thomas F. George
Department of Physics & Astronomy
State University of New York at Buffalo
Amherst, New York 14260

Abstract

Within the framework of the continuum model, the equation of motion for the polarization vector in a semiconductor double heterostructure is solved exactly for the interface phonon modes. Both the eigenvectors and dispersion relations are obtained analytically. It is shown that the slab modes observed in right-angle Raman scattering in a GaAs quantum can be understood in terms of the interface modes found in this paper.

1988 PACS Nos.: 63.20Dj, 68.35.Ja, 78.65.Fa

A-1

## 1. Introduction

The optical phonon spectrum in semiconductor heterostructures and superlattices has been investigated extensively in recent years by Raman scattering experiments. It is by now well recognized that the reduced dimensionality gives rise to phonon modes that are fundamentally different from those in the bulk. In particular, the interface modes [1,2], confined bulk modes[3,4] and confined slab modes [5] have all been observed.

Theoretically, Fuchs and Kliewer [6] examined the optical modes of vibration in the long-wavelength limit for an isolated slab of ionic crystal. They found the surface optical (SO) modes as well as the bulk longitudinal optical (LO) modes. More recently, Wendler [7] considered a double-layer structure and derived interface modes of optical phonons, although the dispersion relations for the interface phonons in a double heterostructure (DHS) were already obtained by Lassnig [8] by means of the energy loss method.

Since the peculiar slab modes reported in Ref. 5 cannot be understood on the basis of any theory mentioned above, the continuum model of lattice vibration was not pursued further. On the other hand, there has not been any rigorous theory based on a microscopic approach except for the linear-chain model [4].

We present in this Letter the theory of interface phonons in a semiconductor DHS using the continuum model. No approximation other than the long-wavelength limit, which is intrinsic in the model, is assumed throughout our calculation. Analytic expressions for the eigenvectors and the dispersion relations are found. It is shown that the symmetric and antisymmetric interface modes each split into two branches at the center of the Brillouin zone, with their frequencies given by $\omega_L$ (the bulk longitudinal optical) and $\omega_T$ (the bulk transverse optical (TO)), respectively. Consequently, lattice

vibrations with longitudinal polarization may occur at the TO frequency and vice versa. A detailed discussion of the theory including the confined bulk modes will be published elsewhere [9].

## 2. Theory

For a DHS with a thin layer of material 1 sandwiched between two thick layers of material 2, the equation of motion for the relative displacement $u(\vec{r},t)$ of the ion pair in material $\nu$ ($\nu = 1,2$) can be written, in the continuum approximation, as

$$\mu_\nu \ddot{\vec{u}}_\nu(\vec{r},t) = -\mu_\nu \omega_{o\nu}^2 \vec{u}_\nu(\vec{r},t) + e^*_\nu \vec{E}(\vec{r},t) \quad , \tag{1}$$

where $\mu$ is the reduced mass of the pair of ions, $\mu\omega_o^2$ is the short-range force constant not including Coulomb fields, $e^*$ *is the effective charge of the ions*, and $\vec{E}(\vec{r},t)$ is the local electric field. The polarization field $\vec{P}(\vec{r},t)$ produced by the oscillating ions is given by

$$\vec{P}(\vec{r},t) = n_\nu e^*_\nu \vec{u}(\vec{r},t) + n_\nu \alpha_\nu \vec{E}(\vec{r},t) \quad , \tag{2}$$

where n is the number of ion pairs per unit cell and $\alpha$ is the polarizability. The local field $\vec{E}$ in (2) is related, in the long-wavelength limit, to the polarization by

$$\vec{E}(\vec{r},t) = \frac{4\pi}{3}\vec{P}(\vec{r},t) + 4\pi \int d\vec{r}'\ \Gamma(\vec{r}-\vec{r}')\cdot\vec{P}(\vec{r}') \quad , \tag{3}$$

where $\Gamma$ denotes the Green tensor with components

$$\Gamma_{\alpha\beta} = \frac{1}{4\pi} \frac{\partial^2}{\partial x_\alpha \partial x_\beta} \frac{1}{|\vec{r}-\vec{r}'|} \quad . \tag{4}$$

If we assume $\vec{P}(\vec{r},t) = \vec{P}(\vec{r})e^{i\omega t}$, we find the equation of motion for the polarization by substituting Eqs. (2) and (3) into (1),

$$\left[\frac{\lambda_\nu - \lambda_{o\nu}}{\alpha_\nu n_\nu(\lambda_\nu - \lambda_{o\nu}) - 1} - \frac{4\pi}{3}\right] \vec{P}(\vec{r}) = 4\pi \int d\vec{r}' \; \Gamma(\vec{r}-\vec{r}')\cdot\vec{P}(\vec{r}') \quad , \tag{5}$$

where we have defined the parameters

$$\lambda_\nu^2 = 4\pi\omega^2/\omega_{p\nu}^2 \quad , \qquad \lambda_{o\nu}^2 = 4\pi\omega_{o\nu}^2/\omega_{p\nu}^2 \quad , \tag{6a,b}$$

with the ion plasma frequency $\omega_{p\nu}^2 = 4\pi n_\nu e_\nu^{*2}/\mu_\nu$.

Since translational symmetry in the z-direction is destroyed by the presence of interfaces, we introduce the two-dimensional vectors $\vec{\kappa}$ and $\vec{\rho}$ so that $\vec{k} = (\vec{\kappa},q)$ and $\vec{r} = (\vec{\rho},z)$. A two-dimensional Fourier transform of (5) then leads to the matrix equation

$$4\pi \begin{bmatrix} \chi_\nu^{-1}(\omega) & 0 & 0 \\ 0 & \chi_\nu^{-1}(\omega) & 0 \\ 0 & 0 & \chi_\nu^{-1}(\omega) \end{bmatrix} \cdot \vec{P}(\vec{\kappa},z)$$

$$= \frac{2\pi}{\kappa} \int_{-\infty}^{\infty} dz' \; e^{-\kappa(z-z')} \; \vec{K}\vec{K}\cdot\vec{P}(\vec{\kappa},z) \tag{7}$$

in which the z-component has been left unchanged, $\vec{K} = [\vec{\kappa}, i\theta(z)\kappa]$ where $\theta(z)$ is the step function, and the function $\chi_\nu^{-1}(\omega)$ is defined by

$$4\pi\chi_{\nu}^{-1}(\omega) = \frac{\lambda_{\nu}-\lambda_{o\nu}}{\alpha_{\nu}n_{\nu}(\lambda_{\nu}-\lambda_{o\nu}) - 1} - \frac{4\pi}{3} \quad . \tag{8}$$

Here $\chi_{\nu}(\omega)$ is the isotropic dielectric susceptibility and is related to the dielectric function $\epsilon_{\nu}(\omega)$ by $\chi_{\nu}(\omega) = \epsilon_{\nu}(\omega) - 1$, where

$$\epsilon_{\nu}(\omega) = \epsilon_{\infty\nu}(\omega_{L\nu}^{2}-\omega^{2})/(\omega_{T\nu}^{2}-\omega^{2}) \tag{9a}$$

$$\epsilon_{\infty\nu}(\omega) = 1 + 4\pi\alpha_{\mu}n_{\nu}/(1 - \frac{4\pi}{3}\alpha_{\nu}n_{\nu}) \quad , \tag{9b}$$

and the LO and TO phonon frequencies are defined by

$$\omega_{L\nu}^{2} = \omega_{o\nu}^{2} + \frac{2}{3}\omega_{p\nu}^{2}/(1 + \frac{8\pi}{3}\alpha_{\nu}n_{\nu}) \tag{10a}$$

$$\omega_{T\nu}^{2} = \omega_{o\nu}^{2} - \frac{1}{3}\omega_{p\nu}^{2}/(1 - \frac{4\pi}{3}\alpha_{\nu}n_{\nu}) \quad . \tag{10b}$$

To describe the propagation of interface phonons, it is more convenient to express the polarization vector as

$$\vec{P}(\vec{\kappa},z) = (\vec{\pi},P_{s}) = (P_{\kappa},\ P_{z},\ P_{s})$$

$$= P_{\kappa}(\vec{\kappa},z)\hat{\kappa} + P_{z}(\vec{\kappa},z)\hat{z} + P_{s}(\vec{\kappa},z)\hat{s} \quad , \tag{11}$$

where the unit vector $\hat{s}$ is defined as $\hat{s} = \hat{z} \times \hat{\kappa}$. Substituting (11) into (7), we can separate the s-component and decouple (7) into the two equations

$$\begin{pmatrix} \chi_v^{-1}(\omega) & 0 \\ 0 & \chi_v^{-1}(\omega)\epsilon_v(\omega) \end{pmatrix} \cdot \vec{\pi}(\vec{\kappa},z) = \frac{1}{4\pi}\int_{-\infty}^{\infty} dz' \; M(z-z')\cdot\vec{\pi}(\vec{\kappa},z') \tag{12}$$

for the so-called p-polarization, and

$$\chi_\nu^{-1}(\omega)\; P_s(\vec{\kappa},z) = 0 \tag{13}$$

for the s-polarization which is not of concern here. The matrix M in (12) is Hermitian and is given by

$$M(z-z') = M^{\dagger}(z'-z) = -\,2\pi\kappa e^{-\kappa|z-z'|} \begin{pmatrix} 1 & i\theta(z-z') \\ i\theta(z-z') & 1 \end{pmatrix} . \tag{14}$$

Equation (12) defines an eigenvalue problem for the normal modes of vibrations. The coupled integral equations can be more easily solved by f..st transforming them into coupled differential equations. Differentiating (12) twice and at the same time requiring a non-vanishing coefficient determinant, we find

$$\frac{d}{dz} P_\kappa(\vec{\kappa},z) = i\kappa P_z(\vec{\kappa},z) \tag{15a}$$

$$\frac{d^2}{dz^2} \vec{\pi}(\vec{\kappa},z) = \kappa^2\vec{\pi}(\vec{\kappa},z) \quad . \tag{15b}$$

The solutions to (16) take the form

$$P_\kappa(\vec{\kappa},z) = \begin{cases} iA_2 e^{\kappa z} & , \quad z < 0 \\ i(A_1 e^{\kappa z} - B_1 e^{-\kappa z}) & , \quad 0 \le z \le a \\ -iB_2 e^{-\kappa z} & , \quad z > 0 \end{cases} \tag{16a}$$

$$P_z(\vec{\kappa},z) = \begin{cases} A_2 e^{\kappa z} & , \quad z < 0 \\ A_1 e^{\kappa z} + B_1 e^{-\kappa z} & , \quad 0 \le z \le a \quad , \\ B_2 e^{-\kappa z} & , \quad z > a \end{cases} \tag{16b}$$

where a is the thickness of material 1. When these solutions are substituted into (12), we find a set of homogeneous equations for the amplitudes $A_\nu$ and $B_\nu$ of the p-polarization. The condition that the determinant for the coefficients must not vanish leads to the dispersion relation

$$\frac{\epsilon_1(\omega) - \epsilon_2(\omega)}{\epsilon_1(\omega) + \epsilon_2(\omega)} = \pm\, e^{\kappa a} \quad , \tag{17}$$

where $\epsilon_1$ and $\epsilon_2$ are given by (9a). The + and - signs on the right-hand side of (17) correspond to the symmetric and antisymmetric modes of the interface phonons, respectively. Remembering (9a) and (17), it is then not difficult to find the explicit eigenvectors for the interface phonon modes from (16). The results are

$$\vec{\pi}_a = \begin{cases} C_a[\frac{\epsilon_2(\omega) - 1}{\epsilon_1(\omega) - 1}]\, e^{\kappa z} \sinh(\frac{\kappa a}{2})(-i, -1) & , \quad z < 0 \\ C_a[i \sinh(\kappa(z-\frac{a}{2})), \cosh(\kappa(z-\frac{a}{2}))] & , \quad 0 \le z \le a \\ C_a[\frac{\epsilon_2(\omega) - 1}{\epsilon_1(\omega) - 1}]\, e^{-\kappa(z-a)} \sinh(\frac{\kappa a}{2})(i, -1) & , \quad z > a \end{cases} \tag{18a}$$

for the antisymmetric modes, and

$$\vec{\pi}_s = \begin{cases} C_s\left[\dfrac{\epsilon_2(\omega) - 1}{\epsilon_1(\omega) - 1}\right] e^{\kappa z} \cosh(\frac{\kappa a}{2})(i,1) \quad , & z < 0 \\ C_s[i \cosh(\kappa(z-a/2)), \sinh(\kappa(z-\frac{a}{2}))] \quad , & 0 \le z \le a \\ C_s\left[\dfrac{\epsilon_2(\omega) - 1}{\epsilon_1(\omega) - 1}\right] e^{-\kappa(z-a)} \cosh(\frac{\kappa a}{2})(i,-1) \quad , & z > a \end{cases} \tag{18b}$$

for the symmetric modes. The normalization constants turn out to be equal to each other, namely,

$$C_a = C_s = \sqrt{\frac{\kappa}{\sinh(\kappa a)} \Big/ \left[\frac{\eta_1}{\omega_{p1}^2} - \frac{\eta_2}{\omega_{p2}^2} \frac{\epsilon_1}{\epsilon_2} \left(\frac{\chi_2}{\chi_1}\right)^2\right]} \quad , \tag{19}$$

where

$$\eta_\nu(\omega_i) = 1/[1 + \alpha_\nu \eta_\nu(\lambda_{o\nu} - \lambda_\nu)]^2 \quad . \tag{20}$$

The explicit dispersion relations follow directly from (9) and (17):

$$\omega_a^{\pm} = \Big\{\epsilon_{\infty 2}(\omega_{T1}^2+\omega_{L2}^2) + \epsilon_{\infty 1}(\omega_{T2}^2+\omega_{L1}^2) \coth(\frac{\kappa a}{2})$$

$$\pm \, (\epsilon_{\infty 2}^2(\omega_{T1}^2-\omega_{L2}^2)^2 + \epsilon_{\infty 1}^2(\omega_{T2}^2-\omega_{L1}^2)^2 \coth^2(\frac{\kappa a}{2})$$

$$+ \, 2\epsilon_{\infty 1}\epsilon_{\infty 2}[(\omega_{T1}^2+\omega_{L2}^2)(\omega_{T2}^2+\omega_{L1}^2)$$

$$- 2(\omega_{T2}^2\omega_{L1}^2+\omega_{L2}^2\omega_{T1}^2)\coth(\frac{\kappa a}{2})])^{\frac{1}{2}}\Big\}^{\frac{1}{2}} \{2[\epsilon_{\infty 2}+\epsilon_{\infty 1}\coth(\frac{\kappa a}{2})]\}^{-\frac{1}{2}} \tag{21a}$$

$$\omega_s^{\pm} = \Big\{\epsilon_{\infty 2}(\omega_{T1}^2+\omega_{L2}^2) + \epsilon_{\infty 1}(\omega_{T2}^2+\omega_{L1}^2)\tanh(\frac{\kappa a}{2})$$

$$\pm (\epsilon_{\infty 2}^2(\omega_{T1}^2-\omega_{L2}^2)^2 + \epsilon_{\infty 1}^2(\omega_{T2}^2-\omega_{L1}^2)^2\tanh^2(\frac{\kappa a}{2})$$

$$+ 2\epsilon_{\infty 1}\epsilon_{\infty 2}[(\omega_{T1}^2+\omega_{L2}^2)(\omega_{T2}^2+\omega_{L1}^2)$$

$$- 2(\omega_{T2}^2\omega_{L1}^2+\omega_{T1}^2\omega_{L2}^2)]\tanh(\frac{\kappa a}{2}))^{\frac{1}{2}}\Big\}^{\frac{1}{2}}\{2[\epsilon_{\infty 2}+\epsilon_{\infty 1}\tanh(\frac{\kappa a}{2})]\}^{-\frac{1}{2}} . \tag{21b}$$

Let us now look at the limiting cases. When $\kappa a \to \infty$, $\tanh(\frac{\kappa a}{2}) = 1$ and $\coth(\frac{\kappa a}{2}) = 1$. Therefore, both (21a) and (21b) approach the same limit which is identical to the result of a bilayer system with only one interface [7], as it should be. The limit $\kappa a \to 0$ yields, of course, the bulk material 2 with frequencies $\omega_{T2}$ and $\omega_{L2}$. When $\kappa a \to 0$, $\tanh(\frac{\kappa a}{2}) = 0$ and $\coth(\frac{\kappa a}{2}) \to \infty$. We then find from (21) that

$$\omega_a^{\pm} = \sqrt{[\omega_{T2}^2+\omega_{L1}^2 \pm (\omega_{T2}^2-\omega_{L1}^2)]/2} = \omega_{T2},\omega_{L1} \tag{22a}$$

$$\omega_s^{\pm} = \sqrt{[\omega_{T1}^2+\omega_{L2}^2 \pm (\omega_{T1}^2-\omega_{L2}^2)]/2} = \omega_{T1},\omega_{L2} \quad , \tag{22b}$$

Thus in the central region of the Brillouin zone, these modes have the same frequencies as those of the bulk LO and TO phonons in each material. For this reason, we shall refer to them as LO-like and TO-like interface phonons.

## 3. Computational Example

As an example, we take GaAs as material 1 and AℓAs as material 2 for our DHS. The dispersion relations calculated from (21) are plotted in Fig. 1.

Many experiments have been performed for this particular type of layered structure. In particular, an experiment of right-angle Raman scattering in a GaAs quantum well [5] reveals novel selection rules for polarization of the incident and scattered light. It is observed that the transverse vibration occurs at the bulk LO frequency of GaAs, while the longitudinal vibration occurs at the bulk TO frequency of GaAs. We show below that this surprising phenomenon can be understood in terms of Raman scattering from interface phonons.

In Raman scattering experiments, the phonon energy is given by the Raman shift, while its momentum is determined by the photon momentum transferred. Under ordinary conditions, the scattering is observed only near the Brillouin zone center. In fact, the experimental parameters involved in Ref. 3 imply $\kappa$ $\sim 0.1$. Therefore, the polarization vector $\vec{\pi}_a$ is dominated by its z-component $P_z^a = C_a \cosh[x(z - a/2)]$ according to (18a), or the antisymmetric interface phonon is predominantly transverse. It follows then from (22a) that the transverse wave in the central layer oscillates at the LO frequency of bulk GaAs. Similarly, we find from (18b) and (22b) that the symmetric interface phonon is predominantly longitudinal and oscillates at the bulk TO frequency of GaAS. A detailed account of this and other experiments will be discussed in forthcoming publications.

In addition to the Raman scattering experiments mentioned above, cyclotron resonance measurements of the electron-phonon interaction have shown pinning phenomena at frequencies below $\omega_L$. In the measurement of the 1s-2p transition energy of hydrogenic impurity confined in a quantum well [10], the pinning is observed at a frequency about 40 $cm^{-1}$ below $\omega_L$, which is 20 $cm^{-1}$ below $\omega_T$. This surprising result has not yet been accounted for theoretically, although the existence of propagating LO modes has been

suggested as a possible origin of zone-folding effects [10]. Our preliminary results of interface phonon modes in a superlattice indicate that it is possible to reproduce experimental data with perhaps some modification of the Frölich coupling constant. More careful study is necessary, however, before any definite conclusion can be made.

## ACKNOWLEDGMENTS

One of us (DLL) would like to thank B. A. Weinstein and J. P. Cheng for useful discussions about the experimental situation and B. D. McCombe for helpful comments. This research was partially supported by the Office of Naval Research and the Air Force Office of Scientific Research (AFSC), United States Air Force, under Contract F49620-86-C-0009. The United States Government is authorized to copy and distribute reprints for governmental purposes notwithstanding any copyright notation hereon.

## REFERENCES

[1] SOOD A. K., MENENDEZ J., CARDONA M. and PLOOG K., Phys. Rev. Lett., 54 (1985) 2115.

[2] GAMMON D., MERLIN R. and MORKOC H., Phys. Rev. B, 35 (1987) 2552.

[3] SOOD A. K., MENENDEZ J., CARDONA M. and PLOOG K., Phys. Rev. Lett., 54 (1985) 2111.

[4] COLVARD C., GANT T. A., KLEIN M. V., MERLIN R., FISCHER R., MORKOC H. and GOSSARD A. C., Phys. Rev. B, 31 (1985) 2080.

[5] ZUCKER J. E., PINCZUK A., CHEMLA D. S., GOSSARD A. and WIEGMANN W., Phys. Rev. Lett., 53 (1984) 1280.

[6] FUCHS R. and KLIEWER K. K., Phys. Rev., 140 (1965) A2076.

[7] WENDLER L., Phys. Status Solidi B, 129 (1985) 513.

[8] LASSNIG R., Phys. Rev. B, 30 (1984) 7132.

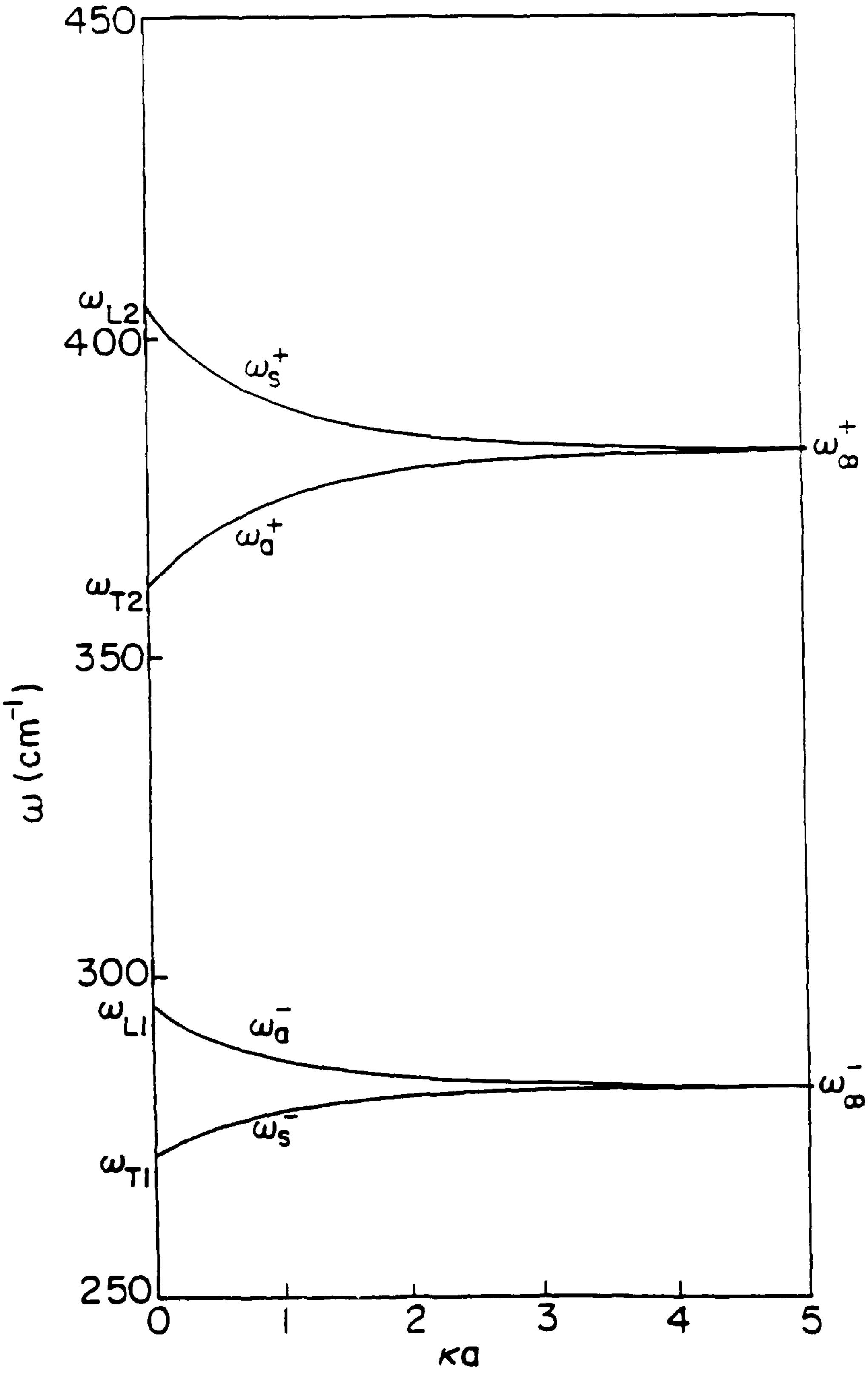
[9] CHEN R., LIN D. L. and GEORGE T. F., to be published.

[10] CHANG Y. H., McCOMBE B. D., MERCY J. M., REEDER A. A., RALSTON J. and WICKS G. A., Phys. Rev. Lett., 61 (1988) 1408.

## FIGURE CAPTION

1. Dispersion relations for the interface modes in GaAs/AlAs double heterostructure for which $\omega_{L2} > \omega_{T2} > \omega_{L1} > \omega_{T1}$.

Fig. 1



TECHNICAL REPORT DISTRIBUTION LIST, GEN

| | No. Copies |
|---|---|
| Office of Naval Research<br>Attn: Code 1113<br>800 N. Quincy Street<br>Arlington, Virginia 22217-5000 | 2 |
| Dr. Bernard Douda<br>Naval Weapons Support Center<br>Code 50C<br>Crane, Indiana 47522-5050 | 1 |
| Naval Civil Engineering Laboratory<br>Attn: Dr. R. W. Drisko, Code L52<br>Port Hueneme, California 93401 | 1 |
| Defense Technical Information Center<br>Building 5, Cameron Station<br>Alexandria, Virginia 22314 | 12 high quality |
| DTNSRDC<br>Attn: Dr. H. Singerman<br>Applied Chemistry Division<br>Annapolis, Maryland 21401 | 1 |
| Dr. William Tolles<br>Superintendent<br>Chemistry Division, Code 6100<br>Naval Research Laboratory<br>Washington, D.C. 20375-5000 | 1 |
| Dr. David Young<br>Code 334<br>NORDA<br>NSTL, Mississippi 39529 | 1 |
| Naval Weapons Center<br>Attn: Dr. Ron Atkins<br>Chemistry Division<br>China Lake, California 93555 | 1 |
| Scientific Advisor<br>Commandant of the Marine Corps<br>Code RD-1<br>Washington, D.C. 20380 | 1 |
| U.S. Army Research Office<br>Attn: CRD-AA-IP<br>P.O. Box 12211<br>Research Triangle Park, NC 27709 | 1 |
| Mr. John Boyle<br>Materials Branch<br>Naval Ship Engineering Center<br>Philadelphia, Pennsylvania 19112 | 1 |
| Naval Ocean Systems Center<br>Attn: Dr. S. Yamamoto<br>Marine Sciences Division<br>San Diego, California 91232 | 1 |
| Dr. David L. Nelson<br>Chemistry Division<br>Office of Naval Research<br>800 North Quincy Street<br>Arlington, Virginia 22217 | 1 |

ABSTRACTS DISTRIBUTION LIST, 056/625/629

Dr. J. E. Jensen
Hughes Research Laboratory
3011 Malibu Canyon Road
Malibu, California 90265

Dr. J. H. Weaver
Department of Chemical Engineering
and Materials Science
University of Minnesota
Minneapolis, Minnesota 55455

Dr. A. Reisman
Microelectronics Center of North Carolina
Research Triangle Park, North Carolina
27709

Dr. M. Grunze
Laboratory for Surface Science and
Technology
University of Maine
Orono, Maine 04469

Dr. J. Butler
Naval Research Laboratory
Code 6115
Washington D.C. 20375-5000

Dr. L. Interante
Chemistry Department
Rensselaer Polytechnic Institute
Troy, New York 12181

Dr. Irvin Heard
Chemistry and Physics Department
Lincoln University
Lincoln University, Pennsylvania 19352

Dr. K.J. Klaubunde
Department of Chemistry
Kansas State University
Manhattan, Kansas 66506

Dr. C. B. Harris
Department of Chemistry
University of California
Berkeley, California 94720

Dr. F. Kutzler
Department of Chemistry
Box 5055
Tennessee Technological University
Cookesville, Tennessee 38501

Dr. D. DiLella
Chemistry Department
George Washington University
Washington D.C. 20052

Dr. R. Reeves
Chemistry Department
Renssaeler Polytechnic Institute
Troy, New York 12181

Dr. Steven M. George
Stanford University
Department of Chemistry
Stanford, CA 94305

Dr. Mark Johnson
Yale University
Department of Chemistry
New Haven, CT 06511-8118

Dr. W. Knauer
Hughes Research Laboratory
3011 Malibu Canyon Road
Malibu, California 90265

ABSTRACTS DISTRIBUTION LIST, 056/625/629

Dr. G. A. Somorjai
Department of Chemistry
University of California
Berkeley, California 94720

Dr. J. Murday
Naval Research Laboratory
Code 6170
Washington, D.C. 20375-5000

Dr. J. B. Hudson
Materials Division
Rensselaer Polytechnic Institute
Troy, New York 12181

Dr. Theodore E. Madey
Surface Chemistry Section
Department of Commerce
National Bureau of Standards
Washington, D.C. 20234

Dr. J. E. Demuth
IBM Corporation
Thomas J. Watson Research Center
P.O. Box 218
Yorktown Heights, New York 10598

Dr. M. G. Lagally
Department of Metallurgical
and Mining Engineering
University of Wisconsin
Madison, Wisconsin 53706

Dr. R. P. Van Duyne
Chemistry Department
Northwestern University
Evanston, Illinois 60637

Dr. J. M. White
Department of Chemistry
University of Texas
Austin, Texas 78712

Dr. D. E. Harrison
Department of Physics
Naval Postgraduate School
Monterey, California 93940

Dr. R. L. Park
Director, Center of Materials
Research
University of Maryland
College Park, Maryland 20742

Dr. W. T. Peria
Electrical Engineering Department
University of Minnesota
Minneapolis, Minnesota 55455

Dr. Keith H. Johnson
Department of Metallurgy and
Materials Science
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Dr. S. Sibener
Department of Chemistry
James Franck Institute
5640 Ellis Avenue
Chicago, Illinois 60637

Dr. Arnold Green
Quantum Surface Dynamics Branch
Code 3817
Naval Weapons Center
China Lake, California 93555

Dr. A. Wold
Department of Chemistry
Brown University
Providence, Rhode Island 02912

Dr. S. L. Bernasek
Department of Chemistry
Princeton University
Princeton, New Jersey 08544

Dr. W. Kohn
Department of Physics
University of California, San Diego
La Jolla, California 92037

ABSTRACTS DISTRIBUTION LIST, 056/625/629

Dr. F. Carter
Code 6170
Naval Research Laboratory
Washington, D.C. 20375-5000

Dr. Richard Colton
Code 6170
Naval Research Laboratory
Washington, D.C. 20375-5000

Dr. Dan Pierce
National Bureau of Standards
Optical Physics Division
Washington, D.C. 20234

Dr. R. Stanley Williams
Department of Chemistry
University of California
Los Angeles, California 90024

Dr. R. P. Messmer
Materials Characterization Lab.
General Electric Company
Schenectady, New York 22217

Dr. Robert Gomer
Department of Chemistry
James Franck Institute
5640 Ellis Avenue
Chicago, Illinois 60637

Dr. Ronald Lee
R301
Naval Surface Weapons Center
White Oak
Silver Spring, Maryland 20910

Dr. Paul Schoen
Code 6190
Naval Research Laboratory
Washington, D.C. 20375-5000

Dr. John T. Yates
Department of Chemistry
University of Pittsburgh
Pittsburgh, Pennsylvania 15260

Dr. Richard Greene
Code 5230
Naval Research Laboratory
Washington, D.C. 20375-5000

Dr. L. Kesmodel
Department of Physics
Indiana University
Bloomington, Indiana 47403

Dr. K. C. Janda
University of Pittsburg
Chemistry Building
Pittsburg, PA 15260

Dr. E. A. Irene
Department of Chemistry
University of North Carolina
Chapel Hill, North Carolina 27514

Dr. Adam Heller
Bell Laboratories
Murray Hill, New Jersey 07974

Dr. Martin Fleischmann
Department of Chemistry
University of Southampton
Southampton 509 5NH
UNITED KINGDOM

Dr. H. Tachikawa
Chemistry Department
Jackson State University
Jackson, Mississippi 39217

Dr. John W. Wilkins
Cornell University
Laboratory of Atomic and
Solid State Physics
Ithaca, New York 14853

OL/1113/86/2

ABSTRACTS DISTRIBUTION LIST, 056/625/629

Dr. R. G. Wallis
Department of Physics
University of California
Irvine, California 92664

Dr. D. Ramaker
Chemistry Department
George Washington University
Washington, D.C. 20052

Dr. J. C. Hemminger
Chemistry Department
University of California
Irvine, California 92717

Dr. T. F. George
Chemistry Department
University of Rochester
Rochester, New York 14627

Dr. G. Rubloff
IBM
Thomas J. Watson Research Center
P.O. Box 218
Yorktown Heights, New York 10598

Dr. Horia Metiu
Chemistry Department
University of California
Santa Barbara, California 93106

Dr. W. Goddard
Department of Chemistry and Chemical Engineering
California Institute of Technology
Pasadena, California 91125

Dr. P. Hansma
Department of Physics
University of California
Santa Barbara, California 93106

Dr. J. Baldeschwieler
Department of Chemistry and Chemical Engineering
California Institute of Technology
Pasadena, California 91125

Dr. J. T. Keiser
Department of Chemistry
University of Richmond
Richmond, Virginia 23173

Dr. R. W. Plummer
Department of Physics
University of Pennsylvania
Philadelphia, Pennsylvania 19104

Dr. E. Yeager
Department of Chemistry
Case Western Reserve University
Cleveland, Ohio 41106

Dr. N. Winograd
Department of Chemistry
Pennsylvania State University
University Park, Pennsylvania 16802

Dr. Roald Hoffmann
Department of Chemistry
Cornell University
Ithaca, New York 14853

Dr. A. Steckl
Department of Electrical and Systems Engineering
Rensselaer Polytechnic Institute
Troy, NewYork 12181

Dr. G.H. Morrison
Department of Chemistry
Cornell University
Ithaca, New York 14853